Comparison of Loss and Crosstalk Characteristics of SOI Based Intersecting Waveguides with Different Bend Structures*

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Abstract By means of two dimension beam propagation method (2D-BPM) with high order Pade approximation, behaviors of SOI waveguide based bend intersections with variant bending radius are simulated and analized. The result shows that crosstalk of intersections decreases with the increase of bending radius and intersecting angle. Furthermore, loss and crosstalk characteristics of bend intersections formed by sine bend, cosine bend and arc bend are compared. Sine bend based structures are proved that it can present lowest loss and smallest crosstalk properties among the three and may find their wide application in the design of bend intersections and other more complicated photonic devices and circuits.

Keywords Guided wave optics; Silicon-on-insulator (SOI); Intersecting waveguide; Waveguide bend

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0 Introduction

Intersecting waveguides are important components in integrated photonics. They not only act as individual devices, such as X-intersecting switches[1~5], but also find their extensive application in switching arrays and other intra-chip connections[6~10]. In the latter case especially, an intersection is seldom constructed by two straight waveguides but by two curved waveguide bends instead.

Sine Bend, Cosine Bend and Arc Bend are widely used S-shape bend structures to realize smooth connections between two parallel straight waveguides with certain lateral displacement[11~14]. Sine Bend and Cosine Bend have more advantages than Arc Bend to reduce bending loss. However, when they are applied to intersections, they also reduce the actual intersection angle and therefore increase crosstalk, thus they should be excluded from the application in intersecting waveguides, as suggested by M. G. Daly et al[15].

According to the analysis, however, intersecting angle is not the only parameter that influences the crosstalk characteristic of bend intersections, and Sine Bend and Cosine Bend are also applied to bend intersections to decrease crosstalk and insertion loss.

In this paper, it focuses on the light transfer properties of bending intersections based on these three bend structures, and the comparison between their loss and crosstalk characteristics. Explanations on the different performances of intersections with different structural parameters and with different bending structures are clearly presented.

1 Intersections with arc bend

The simulation structure in consideration is depicted in Fig. 1 schematically. Two identical S-shaped waveguide bends, with a lateral displacement W and a longitudinal displacement L, intersect with each other at the central point of bends. Four straight waveguides are connected with the bends, serving as inputs and outputs.

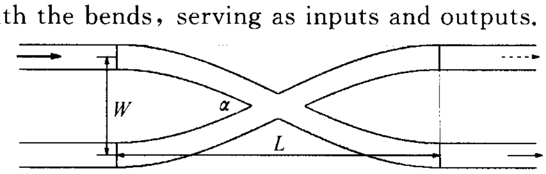

Fig. 1 Schematic view of bend intersection

The analysis is based on the results obtained by means of numerical simulation using 2D-BPM, where high order Pade approximation is used to guarantee the accuracy of simulation, as proved in [16 ~ 18]. The specific intersections in consideration are constructed by SOI based rib waveguides with a rib height of 8 μm, a slab height of 4 μm and a waveguide width of 7 μm, operating at a wavelength of 1.55 μm, which meets the

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single-mode condition for SOI rib waveguides with large cross sections[19]. Prior to the simulation, the rib waveguides are simplified to 2D structures by means of effective index method.

As to arc bends, their bending radius R and intersecting angle α are more easy-understanding variants that determine the structure of bends, both of which can be determined exclusively by W and L. Thus, choose R and α as variants that affect the behavior of intersections. R varies from 1 cm to 4 cm, while α from 5 degree to 20 degree in our consideration, which are typical values in most of the photonic devices.

The variation of insertion loss of intersections with R and α is depicted in Fig. 2. It is mentioned that it deals only with the bending loss and connection loss in the bending structure, while propagation loss, which is mainly caused by sidewall roughness of rib waveguides, is omitted in consideration. It is seen that insertion loss decreases with the increase of R in spite of the consequent increase of waveguide length, which can be explained by the close dependence of bending loss on bending radius. The α dependence of insertion loss, however, is somehow ambiguous according to Fig. 2. It's hard to tell the variation of insertion loss with α in a simple way. This may be attributed to the oscillation of lights in bends caused by mismatch of optical field in joint points. More importantly, this results show that it is bending radius, rather than intersection angle, that dominates the insertion loss of a bending intersection.

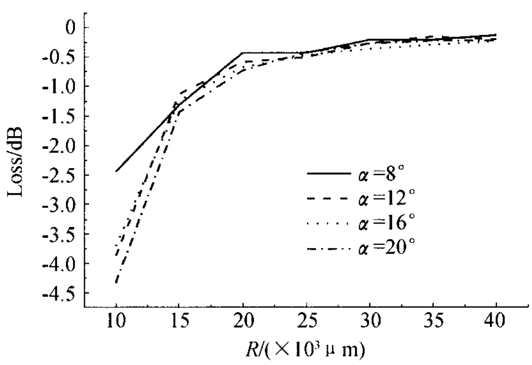

Fig. 2 Loss characteristics of arc—bend based intersections

Fig. 3 shows the crosstalk behavior of bend intersections. It is seen that, besides intersection angle α, bending radius R also makes an obvious contribution to the crosstalk of our structure, which decreases generally with the increase of R and α. As is well known, the larger α is, the harder it is for the light to transfer to the unexpected port in the intersection, and consequently, the smaller the crosstalk will be. The R dependence of crosstalk can be explained by the offset of the center of optical field to that of the waveguide. The smaller the bending radius is, the larger the offset is, the more convenient it is for the light to enter the unexpected waveguide, and thus the larger the crosstalk will be.

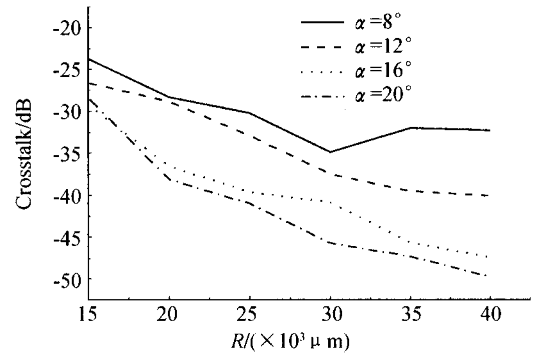

Fig. 3 Crosstalk characteristics of arc—bend based intersections

2 Intersections with sine and cosine bends

Unlike arc bend, the bending radius of Sine Bend and Cosine Bend, however, do not remain constant along arc length at a given W and H (Fig. 4). Therefore, choose W and H as variants to investigate the behavior of intersections constructed by these two bends. The variation of W and H are chosen to be in accordance with that of arc bend in the previous simulation for ease of comparison.

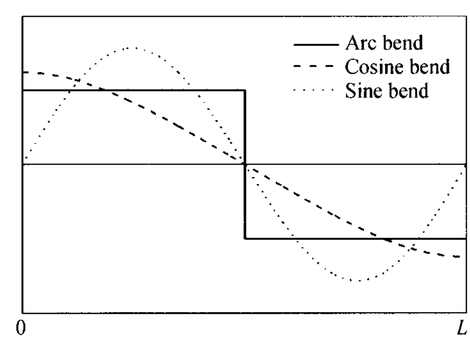

Fig. 4 Curvature variations of arc, cosine, and sine bends along propagation direction

Fig. 4 shows that, at the center of bends, arc bend encounters discontinuity of curvature, which may result in transition loss, while zero transition loss may be acquired in sine bend and cosine bend benefiting from the continuous variation of curvature. Comparison of insertion losses of these three bends is shown in Fig. 5. At a fixed W/H, smaller W corresponds to smaller bend radius, and consequently larger bending loss and transition loss in the waveguide bends. However, at large W, transition loss dominates the total loss, and as a result, sine bend presents the lowest power loss among the three due to the absence of transition losses, as shown in Fig. 5. At small W, however, bending loss makes a major contribution to the total loss, the sine and cosine bends have a larger curvature (smaller bending radius) at certain part than arc bend (Fig. 4), which leads to higher losses than that of arc bend, also shown in Fig. 5.

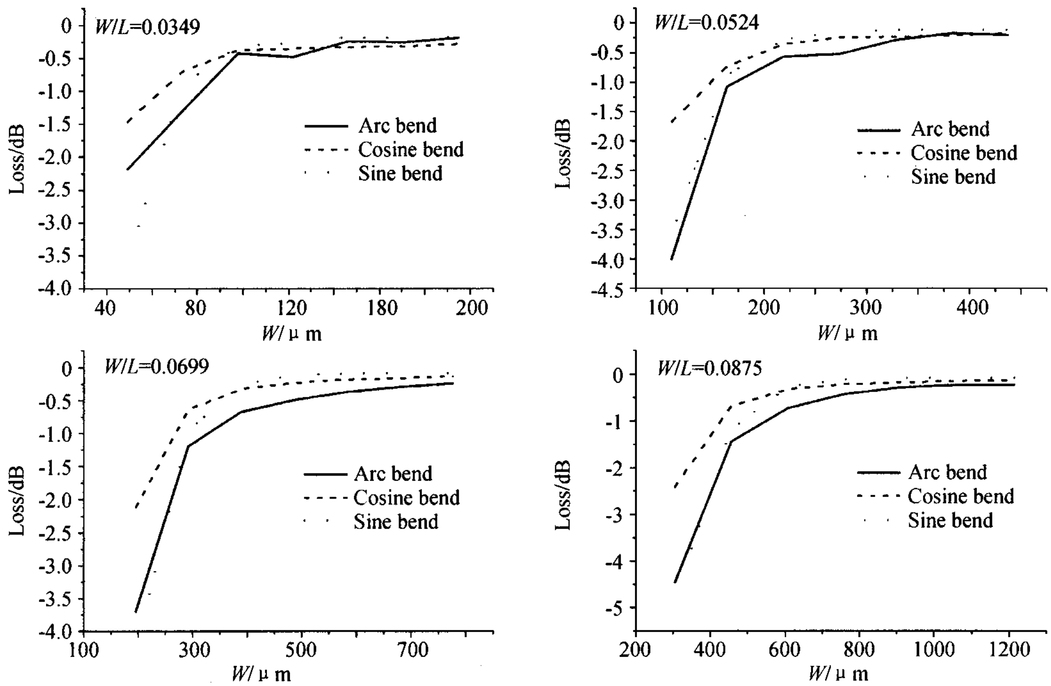

Fig. 5 Comparison of loss characteristics between intersections with three bend structures

According to the above-mentioned point of view, the crosstalk characteristic of a bend intersection is not only related to intersection angle but also to the bending radius at the intersection. Although both sine bend and cosine bend present zero curvature (infinite bending radius) properties at the intersection, cosine bend has a milder curvature variation than sine bend in the region near intersection point. Thus, the crosstalk of cosine bend intersection should be the smallest among the three, while that of arc bend be the largest. However, for these three bend intersections with identical W and H, their intersecting angles are actually different, and their variations with W and H are as follow

$$\alpha_{\cos}=2\arctan\left[\frac{\pi}{2}\frac{W}{L}\right] \tag{1}$$

$$\alpha_{\sin}=2\arctan\left[2\frac{W}{L}\right] \tag{2}$$

$$\alpha_{\mathrm{arc}}=4\arctan\left[\frac{W}{L}\right] \tag{3}$$

where $\alpha_{\cos}$, $\alpha_{\sin}$, α_{arc} are actually intersecting angles in these three bend intersections respectively. Their variations are also shown in Fig. 6. As can be seen , arc bend presents the largest intersecting angle while cosine the smallest, and accordingly, arc bend structure should present the smallest crosstalk while cosine structure the largest, which is exactly contrary to the bending radius caused crosstalk rank. Therefore, the actual crosstalk should be the combination of these two opposite influence caused by these two variants. In consideration, comparison of crosstalk characteristics of these three bend intersections is depicted in Fig. 7. It' s shown that sine bend structure presents the smallest crosstalk among the three, especially at large offsets.

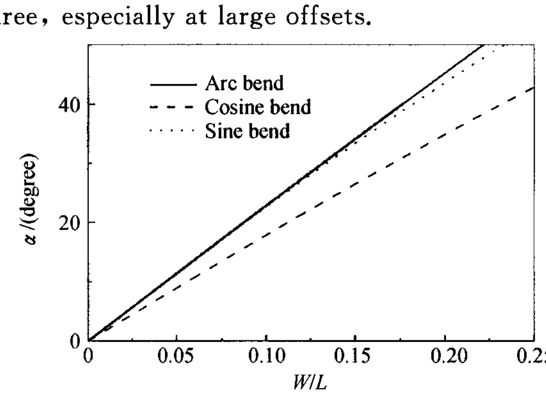

Fig. 6 Variation of actual intersecting angles of three bending intersection with W/L

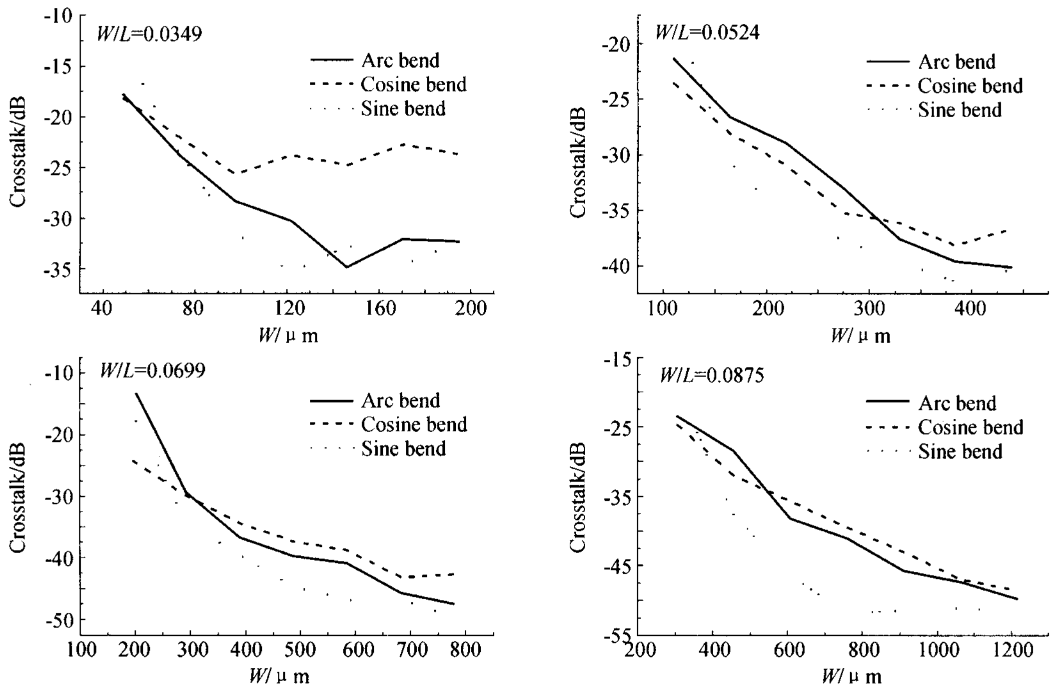

Fig. 7 Comparison of loss characteristics between intersections with three bend structures

In order to achieve high coupling efficiency with the access fiber, the SOI waveguides are designed to have a large cross section and to be weakly guided accordingly. Thus the bending radius of curved waveguides should be large enough to guarantee the low loss propagation of lights. According to the previous analysis, sine bend is preferred in the design of bend intersections to achieve low insertion loss and small crosstalk simultaneously.

3 Conclusion

Insertion loss and crosstalk are two crucial parameters to be considered in the design of integrated photonic devices. As to bend intersection, bending radius and intersecting angle are two major variants that influence the loss and crosstalk characteristic of intersection, which decreases with the increase of bending radius and intersecting angle. Compared with traditional bend intersections constructed by arc bend, application of sine and cosine bends to bend intersections may increase the actual bending radius at the intersecting region, while decrease the actual intersecting angle at the same time. Accordingly, the eventual crosstalk is the combination of these two opposite contributions. Therefore, sine bend and cosine bend should not be excluded in the formation of bend intersections. Together with their loss reduction property, sine and cosine bends may also be applied in the bend intersection to achieve small crosstalk at the same time.

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不同结构SOI交叉波导的损耗及串扰特性研究

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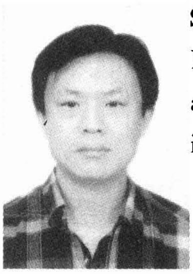
摘 要 利用高阶Pade近似的2D-BPM算法,对具有不同弯曲半径及交叉角度的SOI弯曲交叉波导的传输特性进行了模拟、分析和深入研究,发现交叉波导的串扰随弯曲半径及交叉角度增大而减小的规律.在此基础上,对由正弦弯曲、余弦弯曲以及圆弧弯曲三种弯曲波导构成的SOI交叉波导的损耗及串扰特性进行了分析比较.结果表明,由正弦弯曲构成的交叉波导传输损耗最小且串扰最小.

关键词 导波光学;SOI;交叉波导;弯曲波导



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